Accretion disk assembly and survival during the disruption of a neutron star by a black hole

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Abstract. We study the formation of accretion disks resulting from dynamical three dimensional binary coalescence calculations, where a neutron star is tidally disrupted before being swallowed by its black hole companion. By subsequently assuming azimuthal symmetry we are able to follow the time dependence of the disk structure for a few tenths of a second. Although the disruption of a neutron star leads to a situation where violent instabilities redistribute mass and angular momentum within a few dynamical timescales, enough gas mass remains in the orbiting debris to catalyse the extraction of energy from the hole at a rate adequate to power a short-lived gamma ray burst.

1. Short-lived mysteries

Almost 5 years after astronomers first discovered their telltale afterglows, the brief, ultrabright flashes of high-energy radiation known as cosmic gamma-ray bursts (GRBs) are still among the most mysterious phenomena in the universe. Their energy output has to be of the order $10^{51} - 10^{54}$ erg s^{-1}, larger than that of any other type of source. Most researchers agree that the most common GRBs – those that last between about a second and a minute – signal the catastrophic collapse of massive, rapidly rotating stars into black holes (see Mészáros 2001 for a review). The precise details of their origin, however, are unknown; and the nature of bursts that flash in less than a second is anybody's guess. These bursts, which account for about one-third of all observed GRBs, differ markedly from the long ones not only in duration but also in having a larger proportion of high-energy gamma rays in their energy distribution. The most widely favoured and conventional possibility is that they result either from the merger of two neutron stars or of a neutron star and a black hole (e.g. Narayan et al. 1992).

When a neutron star is tidally disrupted by a black hole, the total angular momentum is large enough for the star not to be swallowed immediately. The expected outcome, after a few milliseconds, would therefore be a spinning black hole, orbited by a torus of neutron-density matter. An acceptable model thus requires that the surrounding torus should not completely drain into the hole, or be otherwise dispersed, on too short a time scale (Rees 1999). The key issue

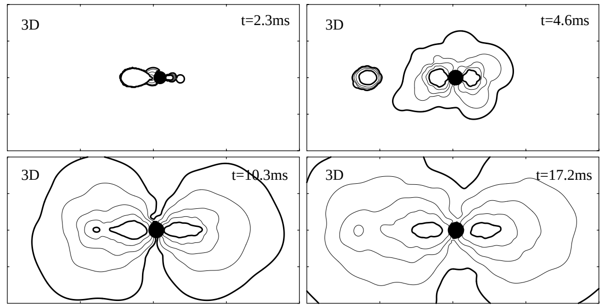

Figure 1. Sequence of images of the tidal disruption of a neutron star by a black hole in a close binary, showing density contours in a meridional slice (3D calculation). All contours are logarithmic and equally spaced $\log \rho = 8 - 12$ in cgs units. Bold contours are plotted at $\log \rho = 8, 12$. Each box size is 400 km $\times$ 200 km.

is then how long a sufficient amount of this matter survives to power a burst, and it is to this problem that we have turned our attention.

2. Coalescing odd couples

It has been our objective to investigate the outcome of the coalescence of a black hole with a neutron star, to find out to what extent the neutron star is tidally disrupted and, in particular, to determine if an accretion structure does form around the black hole as a result of the encounter. Using a three-dimensional smooth particle hydrodynamics (SPH) code we have simulated the last stages of binary evolution of a black hole and a neutron star, when the components are separated by a few stellar radii. The gravitational radiation waveforms as well as the gravitational radiation luminosity are calculated in the quadrupole approximation; and the neutron star is modeled with a stiff polytropic equation of state (the reader is referred to Lee 2001 for further details). Given that tidal locking is not expected in these systems (e.g. Bildsten & Cutler 1992), we have used initial conditions that correspond to irrotational binaries in equilibrium, approximating the neutron star as a compressible triaxial ellipsoid.

The 3D dynamical simulations are begun when the system is on the verge of initiating mass transfer, and followed for approximately 22 ms. The decrease in binary separation leads to Roche lobe overflow on an orbital time-scale. A stream of gas forms at the inner Lagrange point, transferring matter from the neutron star to the black hole. At the same time, the star is tidally stretched and extends away from the black hole through the external Lagrange point. Figure 1 shows the density contours in a meridional slice at various times during the simulation.

As the accretion stream winds around the black hole, it collides with itself and forms a torus, while the gas thrown out through the outer Lagrange point forms a long tidal tail. The orbiting debris that is formed around the black hole is not initially azimuthally symmetric, but shows a double ring structure. This appears as the gas that passes through periastron near the black hole overshoots

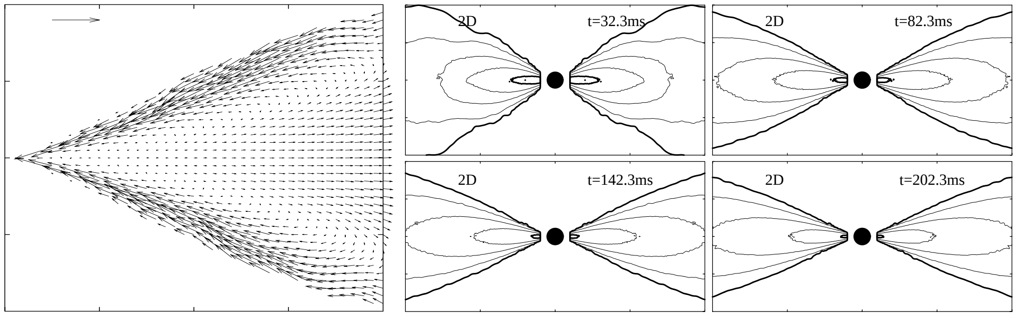

Figure 2. Dynamical evolution of a massive accretion disk around a stellar mass black hole in two dimensions (azimuthal symmetry). *Left:* Velocity field at $t = 82.3$ ms. The vector at top left has $v = 5 \times 10^8 \mathrm{cm\ s}^{-1}$. *Right:* logarithmic density contours as those shown in Fig. 1.

the circular orbit that would correspond to the specific angular momentum it contains, forming an outer ring. It then falls back towards the black hole and encounters the rear of the accretion stream. The subsequent collision tends to circularize the orbit of the fluid, and also pushes it to the inner ring, closer to the black hole. The structure of the outer ring and the bulk of the disrupted star continue their orbital motion on opposite sides of the black hole. At late times, the disc becomes more azimuthally symmetric.

3. Survival of the orbiting debris

A question which has remained largely unanswered so far is what determines the characteristic duration of bursts, which can extend to tens, or even hundreds, of seconds. This is of course very long in comparison with the dynamical or orbital time scale. The disruption of a neutron star is almost certain to lead to a situation where violent instabilities redistribute mass and angular momentum within a few dynamical time scales. A key issue is then the nature of the surviving debris after these violent processes are over.

So far, though, attempts to calculate such an evolution have run up against the lack of multi–dimensional, time–dependent simulations. There is now a stronger motivation to develop models in fuller detail. This paper outlines the behavior of the accretion structures on timescales that are much longer than the dynamical one. By assuming azimuthal symmetry we are able to map the output from the 3D calculation described above to 2D, and thus follow the time dependence of the disk structure on timescales that are comparable to the durations of short bursts (in this case for an additional 200 ms). We use Newtonian physics, an ideal gas equation of state, and solve the equations of viscous hydrodynamics assuming an α law. All the energy dissipated by the physical viscosity is radiated away in neutrinos (Lee & Ramirez-Ruiz 2002).

We find that meridional circulations are promptly established, whose structure depends mainly on the value of α. There is an important motion of fluid from the inner regions of the disks to large radii, along the equatorial plane. The flow is directed toward the accreting black hole along the surface of the disk and in the equatorial region at small radii (Fig. 2 shows the evolution for $\alpha = 0.1$). The disks remain thick ($H/R \sim 0.5$) throughout the dynamical evolution, due to their large internal energy, with accretion rates on the order of 1 $M_{\odot}\mathrm{s}^{-1}$. The maximum densities decrease during our calculations, as there is no external agent feeding the disks, but remain at $\sim 10^{12}\mathrm{g\ cm}^{-3}$, with corresponding internal energy densities $\sim$ few $\times 10^{30}\mathrm{ergs\ cm}^{-3}$.

There are several instabilities that can affect massive accretion disks dynamically and shorten their lifetimes considerably, compared with the viscous timescale. These instabilities can be virulent in a torus where the specific angular momentum is uniform throughout, but are inhibited by a spread in angular momentum. In a torus that was massive and/or thin enough to be self-gravitating, bar-mode gravitational instabilities could lead to further redistribution of angular momentum and/or to energy loss by gravitational radiation within only a few orbits. Whether a torus of given mass is dynamically unstable depends on its thickness and stratification, which in turn depends on internal viscous dissipation and neutrino cooling (Narayan et al. 2001).

From our simulations we draw the following conclusions. First, we find that the central object survives the initial, violent event that created it – the total angular momentum is large enough for the star not to be swallowed immediately. Second, the orbiting debris is stable to both radial and axisymmetric perturbations. Third, even if the evolution time scale for the bulk of the debris torus were no more than a tenth of a second, enough may remain to catalyse the extraction of energy from the hole at rate adequate to power a short-lived burst. However, these simulations clearly cannot tackle directly other relevant issues, mainly related to the evolution of the magnetic field, and its influence on the dynamics.

Magnetic instabilities could make the disk lifetime much shorter by effectively increasing the viscosity. The amplification of the magnetic field may be self–limiting due to magnetic stress, which would cause disk flaring. The properties of the expected variability depend strongly on the details of the configuration of the disk corona (e.g. Thompson 1994) generated by the magnetic field, which is removed from the disk by flux buoyancy.

References

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